TITLE OF THE INVENTION

METHOD AND SYSTEM FOR BLIND KARHUNEN-LOEVE TRANSFORM CODING

CROSS-REFERENCE TO CO-PENDING APPLICATIONS

The present application is related to and claims priority to U.S. Provisional Application Serial No. 60/239,930, filed October 13, 2000. The contents of that application are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the field of signal coding, and more specifically to Karhunen-Loeve transform coding.

Discussion of the Background

Transform coding is a known technology for coding signals. Figure 1 shows a block diagram of a conventional transform coder, including a transmitter 10 and a receiver 11. At the transmitter 10, an original discrete-time signal frame x_n is transformed by a transformer 100 into transform coefficients y_n. Each signal frame x_n, for $n = 1, 2, 3, \ldots$ is generally comprised of a continuous segment of length N of a discrete-time signal $x(k)$ and can be defined, for example, as $x_n = [x(nN-1)\ x(nN-2)\ \ldots\ x(N(n-1))]^T$. Further, the segments of the signal $x(k)$ defining the signal frames x_n can overlap up to $N-1$ elements or be totally non-overlapping.

The transformation preferably decorrelates the original signal frame and compacts a large fraction of the signal energy, i.e. variance, into relatively fewer transform coefficients. This is known as an energy-packing property. Because of this property, it is possible to retain a fraction of the transform coefficients without seriously affecting the reconstructed signal quality. The transform coefficients are quantized at the quantizer 110 to yield the quantized transform coefficients $\hat{y}_n$. As a result of quantization and the possible elimination of redundant transform coefficients, the quantized signal $\hat{y}_n$ that is encoded by the encoder

120 may contain significantly less than the N elements in the original signal frame x_n. The encoded signal is then sent along the channel.

At the receiver 11, the encoded signal is received through the channel into the decoder 130. The signal is decoded, yielding the quantized transform coefficients $\hat{y}_n$. The original signal frame is reconstructed at the inverse transformer 140 to produce the reconstructed signal frame $\hat{x}_n$. Because the transform coefficients were quantized and some redundant or insignificant transform coefficients were possibly eliminated prior to encoding, the reconstructed signal frame $\hat{x}_n$ is generally slightly different from the original signal frame x_n.

The Karhunen-Loeve transform (KLT) is known to be the optimum transform for signal compression because the KLT exhibits a significant energy-packing property. In other words, a larger fraction of the total energy or variance of the signal frame is contained in the first few coefficients, as compared to other transforms. Therefore, the number of transform coefficients retained, quantized, and encoded can be significantly less than other transforms. As a result, the signal bit rate during transmission is reduced while the signal quality is maintained. More details concerning the KLT are found in Digital Coding of Waveforms, by N. Jayant and P. Noll, 1984, the entire contents thereof incorporated herein by reference. Additional information about KLT may also be found in (1) C.E. Davila, "Blind Adaptive Estimation of KLT Basis Vectors", Transactions on Signal Processing, Vol. 49, No. 7, pgs. 1364-1369, July, 2001; (2) C.E. Davila, "Blind KLT Coding," Proc. 2000 IEEE Signal Processing Workshop, Hunt, Texas, October 15-18, 2000 (the proceedings of which are available via HTTP at "spib.rice.edu/SPTM/DSP2000/submission/DSP/papers/paper153/paper153.pdf"); and (3) C.E. Davila, "Blind Adaptive Estimation of KLT Basis Vectors," Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing, Istanbul, June 5-9, 2000. The contents of those papers are incorporated herein by reference.

In the transformer 100, the KLT transform coefficients y_n are determined by applying a KLT transform matrix Q to the original signal x_n, as shown in Equation (1),

$$y_n = Q\,x_n. \qquad (1)$$

The net effect of the transformation is to establish a new coordinate system whose origin is at the centroid of the population of the original signal frame x_n and whose axes are in the direction of the eigenvectors of the autocorrelation matrix R of the original signal frame x_n.

The eigenvalues are the variances, i.e., original signal energy, of the KLT transform coefficients y_n along the eigenvectors. The eigenvectors form the column vectors of the transform matrix Q, and are also referred to as KLT basis vectors.

Unfortunately, the KLT basis vectors are data-dependent, i.e., they require an estimate of the autocorrelation matrix of the original signal frame x_n for their computation. Hence, in order to reconstruct the original signal frame at the receiver 11, the KLT basis vectors must also be encoded with the KLT transform coefficients and transmitted to the receiver. The necessity of transmitting the KLT basis vectors reduces signal compression and leads to increased bit rates. For this reason, the KLT has had limited use in signal coding algorithms.

SUMMARY OF THE INVENTION

Accordingly, one object of the present invention is to provide a method and system to use the Karhunen-Loeve transform to encode, transmit, and accurately reconstruct a signal frame without suffering a reduction in signal compression or increased bit rates.

A further object of the present invention is provide a method and system to encode and transmit KLT coefficients, without having to encode and transmit KLT basis vectors.

Another object of the present invention is to estimate basis vectors from the KLT transform coefficients at the receiver.

Another object of the present invention is to provide a method and system to reconstruct the original signal frame using the estimated KLT basis vectors at the receiver.

These and other objects are accomplished by way of a KLT coding method, system, and computer program product constructed according to the present invention, wherein the KLT transform coefficients of an original signal frame are calculated at a transmitter, the KLT coefficients are transmitted to a receiver, KLT basis vectors of the original signal are estimated at the transmitter and the receiver based on the KLT transform coefficients, and the original signal frame is reconstructed at the receiver from the estimated KLT basis vectors, thereby performing "blind" KLT coding. This is called "blind" KLT coding because the receiver estimates the KLT basis vectors without explicit knowledge of the original signal frame x_n.

Thus, according to the "blind" KLT coding of the present invention, the KLT transform coefficients are encoded and transmitted, without the corresponding KLT basis

vectors, to a receiver, at which the signal frame is successfully reconstructed.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

Figure 1 is a block diagram of a conventional transform coder which transforms, quantizes, and encodes an original signal at a transmitter and which receives, decodes, inversely transforms the transmitted signal at a receiver;

Figure 2A is a flowchart of the steps performed at the transmitter in a first embodiment of the invention in which the KLT basis vectors are estimated from the transform coefficients;

Figure 2B is a flowchart of the steps performed at the receiver in the first embodiment of the invention in which the KLT basis vectors are estimated from the transform coefficients;

Figure 2C is an exemplary algorithm of the first embodiment of the invention in which the KLT basis vectors are estimated from the transform coefficients;

Figure 3 is a graph showing an exemplary result of the first embodiment of Figures 2A-2C;

Figure 4A is a flowchart of the steps performed at the transmitter in a second embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and a codebook index;

Figure 4B is a flowchart of the steps performed at the receiver in the second embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and a codebook index;

Figure 4C is an exemplary algorithm of the second embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and a codebook index;

Figure 5 is a graph showing an exemplary result of the second embodiment of Figures 4A-4C;

Figure 6A is a flowchart of the steps performed at the transmitter in a third

embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and the number of KLT transform coefficients;

Figure 6B is a flowchart of the steps performed at the receiver in the third embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and the number of KLT transform coefficients;

Figure 6C is an exemplary algorithm of the third embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients and the number of KLT transform coefficients;

Figure 7 is a graph illustrating an exemplary comparison between the original signal and the reconstructed signal produced by the embodiment of Figures 6A-6C;

Figure 8A is a flowchart of the steps performed at the transmitter in a fourth embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients, the number of KLT coefficients, and the number of bits per coefficient;

Figure 8B is a flowchart of the steps performed at the receiver in the fourth embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients, the number of KLT coefficients, and the number of bits per coefficient;

Figure 8C is an exemplary algorithm of the fourth embodiment of the invention in which the KLT basis vectors are estimated based on the transform coefficients, the number of KLT coefficients, and the number of bits per coefficient;

Figure 9 is a graph illustrating an exemplary result of the fourth embodiment of Figures 8A-8C;

Figure 10A is a flowchart of the steps performed at the transmitter in a fifth embodiment of the invention;

Figure 10B is a flowchart of the steps performed at the receiver in the fifth embodiment of the invention;

Figure 10C is an exemplary algorithm of the fifth embodiment of the invention; and

Figure 11 is a block diagram of a transform coder using KLT coding of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views.

Estimation of the KLT basis vectors can be accomplished by estimating the autocorrelation matrix $\hat{R}_n$ of an original signal frame x_n, updating that estimate $\hat{R}_n$ each time a new signal frame is obtained, and estimating the eigenvectors and eigenvalues of the autocorrelation matrix $\hat{R}_n$. Recall that the eigenvectors of the autocorrelation matrix are the KLT basis vectors arranged in transform matrix Q, such that the *estimated* KLT eigenvector and corresponding KLT eigenvalue matrices of $\hat{R}_n$ are $\hat{Q}_n$ and $\hat{\Lambda}_n$, respectively. The estimation process is iterative such that the KLT basis vectors estimated for a current signal frame x_n can be used to calculate the KLT transform coefficients of the next signal frame x_{n+1}. Then, the KLT basis vectors are estimated for the next signal frame x_{n+1} and used to calculate the KLT transform coefficients of the signal frame x_{n+2}, and so forth.

The transmitter and the receiver of the present invention both estimate the KLT basis vectors, i.e., matrix $\hat{Q}_n$. The transmitter calculates the KLT transform coefficients y_n based on the previously estimated KLT basis vectors, matrix $\hat{Q}_{n-1}$, and transmits these KLT transform coefficients to the receiver. The receiver then reconstructs the original signal frame from these KLT transform coefficients y_n by multiplying the KLT transform coefficients by the inverse of the estimated KLT basis vectors, matrix $\hat{Q}_{n-1}$. As such, the KLT basis vectors at the transmitter and the receiver are the same. This feature allows the present invention to transmit the KLT coefficients without the corresponding KLT basis vectors.

Figures 2A-2C show a first embodiment of the method of KLT coding of the present invention in which the KLT coefficients are transmitted to the receiver in order to reconstruct the original signal frame.

Figure 2A shows the steps performed at the transmitter in the method of the first embodiment. In step S210, the KLT basis vector matrix $\hat{Q}$, is initialized to the first r columns of an N by N identity matrix and the KLT eigenvalue matrix $\hat{\Lambda}$ is initialized to an r by r identity matrix. The integer r is a predetermined positive integer. Note that the KLT basis vectors are initialized to orthonormal vectors.

In step S212, a search direction vector $\vec{v}_n$ is selected. The search direction represents a direction in space to be searched in order to eventually reach the true KLT basis vectors of

the original signal frame. In this embodiment, the search direction vector $\vec{v}_n$ is set to a white noise vector, for example.

In step S214, the KLT basis vector matrix $\hat{Q}_n$ is expanded accordingly to include the search direction vector $\vec{v}_n$ to produce $\bar{Q}_n$.

In step S216, the transform coefficients y_n are calculated from the previously estimated basis vector matrix $\hat{Q}_{n-1}$, prior to expansion, and the original signal frame x_n according to Equation (2):

$$y_n = \hat{Q}_{n-1}^T x_n \qquad (2)$$

In step S218, the transform coefficients are updated to include a scalar component corresponding to the search direction vector $\vec{v}_n$ to produce $\bar{y}_n$.

In step S219, the updated transform coefficients $\bar{y}_n$ are quantized to produce $\hat{y}_n$.

In step S220, the updated transform coefficients $\hat{y}_n$ are transmitted to the receiver. Note that he number of bits allocated to encode each KLT transform coefficient may be predetermined or calculated using, for example, the optimal scheme given by Equation (9). Moreover, additional optional information may be transmitted to the receiver along with the KLT transform coefficients and this information may include data regarding the bit allocation scheme.

In step S222, the matrices F and G are calculated. F is an updated estimate of the autocorrelation matrix, where $\hat{Q}_{n-1}$ is the previously estimated KLT basis vector matrix and $\hat{\Lambda}_{n-1}$ is the corresponding KLT eigenvalue matrix. Equation (3a) is a calculation of F:

$$F = \gamma \bar{Q}_n^T \hat{Q}_{n-1} \hat{\Lambda}_{n-1} \hat{Q}_{n-1}^T \bar{Q}_n + \hat{y}_n \hat{y}_n^T \qquad (3a)$$

in which γ is a constant between 0 and 1, $\bar{Q}_n$ is the expanded KLT basis vectors matrix from step S214, and y_n are the quantized KLT transform coefficients. G is an associated matrix calculated according to Equation (3b):

$$G = \bar{Q}_n^T \bar{Q}_n \, . \qquad (3b)$$

After F and G are calculated, they define the generalized eigenvalue problem shown in Equation (4):

$$FW_n = GW_n\Pi_n \qquad (4)$$

in which W_n and Π_n are the respective updated eigenvectors and eigenvalues of the autocorrelation matrix.

In step S224, using standard techniques, the generalized eigenvalues problem is solved for W_n and Π_n. Details of standard techniques are described in <u>Matrix Computations</u> by Golub and Van Loan, 1989, the entire contents thereof incorporated herein by reference.

In step S226, the KLT basis vector matrix and the corresponding eigenvalue matrix are updated using W_n and Π_n. Hence, the KLT basis vectors are estimated at the transmitter.

Steps S212-S226 are repeated for all additional signal frames.

Figure 2B shows the steps performed at the receiver in the method of the first embodiment. In step S250, the KLT basis vector matrix $\hat{Q}$ is initialized to the first r columns of an N by N identity matrix and the KLT eigenvalue matrix $\hat{\Lambda}$ is initialized to an r by r identity matrix. The integer r is the same predetermined positive integer used by the transmitter.

In step S252, a search direction vector $\vec{v}_n$ is selected. The search direction vector of the transmitter and the receiver are the same.

In step S254, the basis vector matrix $\hat{Q}_n$ is expanded accordingly to include the search direction vector $\vec{v}_n$ to produce $\bar{Q}_n$.

In step S256, the transform coefficients $\hat{y}_n$ are received from the transmitter. Note that additional optional information may also be received at this step, including information regarding the bit allocation scheme used to encode the KLT transform coefficients.

In step S258, the reconstructed signal $\hat{x}_n$ is found according to Equation (5a):

$$\hat{x}_n = \hat{Q}_{n-1}\hat{y}_n(1:r) \qquad (5a)$$

in which y_n are transform coefficients and $\hat{Q}_{n-1}$ is the previously estimated KLT basis vector matrix, prior to expansion.

Steps S262-S266 are similar to the steps S222-S226 performed by the transmitter to

estimate the KLT basis vectors. As such, the receiver can estimate the KLT basis vectors and reach the same estimate as the transmitter. Thus the receiver can estimate the KLT basis vectors and use them to reconstruct the original signal successfully without having received the basis vectors from the transmitter.

Steps S252-S266 are repeated for all additional signal frames.

Figure 2C shows an exemplary algorithm for performing KLT coding in the first embodiment.

Figure 3 is a graph showing an exemplary result of the first embodiment of the present invention. A signal $x(n)$ is defined as

$$x(n) = \begin{cases} \cos(0.35\pi n)+\cos(0.78\pi n+0.35\pi), & n=1,\ldots,999 \\ \cos(0.6\pi n)+\cos(0.8\pi n+0.35\pi), & n=1000,\ldots,2000 \end{cases} \qquad (5a)$$

The mean squared error, defined in Equation (5b),

$$\epsilon^{0}(n) \equiv \left|\left|\hat{x}_n - x_n\right|\right|^2 \qquad (5b)$$

is an estimate of the difference between the original signal frame and the reconstructed signal frame, for different signal frame lengths N. Note that for this result, each signal frame x_n is defined with the maximum possible overlap of $N-1$ signal elements. The results in Figure 3 show that the mean squared error is very low initially and continues to decrease as n increases. At $n=1000$, $\epsilon^{0}(n)$ increases because the signal pattern changes. However, the error is still low and decreasing. Thus, the reconstructed signal is very close to the original signal.

Figures 4A-4C show a second embodiment of the method of KLT coding of the present invention. In this embodiment, an optimal search direction vector is found from a predetermined set of possible search directions. The optimal search direction vector is the one that maximizes the trace of the eigenvalue matrix Π_n. The trace of the eigenvalue matrix indicates the magnitude of the eigenvalues. The trace should be maximized as an indication that the total energy of the eigenvalues is relatively large. Large eigenvalues indicate a good selection for the Q matrix and a good decorrelation of the original signal frame in obtaining the KLT transform coefficients. Instead of setting the search direction vector to, for example, a white noise vector as in the previous embodiment, an identical list

or codebook of candidate search direction vectors is stored at both the transmitter and receiver.

Figure 4A shows the steps performed at the transmitter in the method of the second embodiment. In step S410, the KLT basis vector matrix $\hat{Q}$, is initialized to the first r columns of an N by N identity matrix and the KLT eigenvalue matrix $\hat{\Lambda}$ is initialized to an r by r identity matrix. The integer r is a predetermined positive integer. Note that the KLT basis vectors are initialized to orthonormal vectors.

In step S412, a search direction vector $\vec{v}_n$ is selected from the codebook. The order of the selection may be random, sequential, or based on some specific ordering.

In step S414, the basis vector matrix $\hat{Q}_n$ is expanded accordingly to include the search direction vector to produce $\bar{Q}_n$.

In step S416, the transform coefficients y_n are calculated from the previously estimated basis vector matrix $\hat{Q}_{n-1}$, prior to expansion, and the original signal x_n according to Equation (2).

In step S418, the transform coefficients are updated to include a scalar component corresponding to the search direction vector $\vec{v}_n$ to produce $\bar{y}_n$.

In step S420, the updated transform coefficients $\bar{y}_n$ are quantized to produce $\hat{y}_n$.

In step S422, eigenvector matrices F and G are calculated, as in Equations (3a) and (3b).

In step S424, following Equation (4), using standard techniques, the generalized eigenvalues problem is solved for W_n and Π_n .

In step S426, the KLT basis vector matrix and the corresponding eigenvalues are updated using W_n and Π_n.

In step S428, the trace of Π_n is calculated.

In step S429, an inquiry is made whether the calculated trace is greater than a given value. If the trace is not greater than the given value, then step S431 is performed. However, if the trace is greater than the given value, then, in step S430, the calculated trace becomes the given value, the index of the search direction vector in the codebook is stored, the corresponding KLT coefficients are stored, and step S431 is performed.

In step S431, an inquiry is made whether all search vectors in the codebook have been selected. If not, steps S412-S429 are performed. Otherwise, step S432 is performed.

In step S432, both the quantized transform coefficients $\hat{y}_n$ and the codebook index m_o

of the search direction vector corresponding to the maximum calculated trace are transmitted to the receiver. Note that he number of bits allocated to encode each KLT transform coefficient may be predetermined or calculated using, for example, the optimal scheme given by Equation (9). Moreover, additional optional information may be transmitted to the receiver along with the KLT transform coefficients and this information may include data regarding the bit allocation scheme.

Steps S412-S432 are repeated for all additional signal frames.

Figure 4B shows the steps performed at the receiver in the method of the second embodiment. In step S450, the KLT basis vector matrix $\hat{Q}$, is initialized to the first r columns of an N by N identity matrix and the KLT eigenvalue matrix $\hat{\Lambda}$ is initialized to an r by r identity matrix. The integer r is the same predetermined positive integer used by the transmitter.

In step S452, the quantized transform coefficients $\hat{y}_n$ and the codebook index m_o are received from the transmitter. Note that additional optional information may also be received at this step, including information regarding the bit allocation scheme used to encode the KLT transform coefficients.

In step S454, the reconstructed signal $\hat{x}_n$ is found from Equation (5).

In step S456, the optimum search direction vector $\vec{v}_n$ is retrieved from the codebook. Recall that the codebooks of the transmitter and the receiver are the same.

In step S458, the basis vector matrix $\hat{Q}_n$ is expanded accordingly to include the optimum search direction vector to produce $\overline{Q}_n$.

Steps S462-S472 are similar to steps S422-S426 performed by the transmitter to estimate the KLT basis vectors. As such, the receiver can estimate the KLT basis vectors and reach the same estimate as the transmitter. Thus the receiver can estimate the KLT basis vectors and use them to reconstruct the original signal frame successfully without having received the KLT basis vectors from the transmitter.

Steps S452-472 are repeated for all additional signal frames.

Figure 4C shows an exemplary algorithm for performing KLT coding in the second embodiment.

Figure 5 is a graph showing an exemplary result of the second embodiment of the present invention. Similar to Figure 3, the mean squared error $\epsilon^0(n)$ for different signal frame lengths N is shown as a function of n for the signal defined in Equation (5a). In this

case, the mean squared error decreases rapidly because the optimum search direction vector results in faster convergence toward the true KLT basis vectors. Again, at $n=1000$, $\epsilon^0(n)$ increases because the signal pattern changes. However, the error is still low and decreasing. Thus, the reconstructed signal is very close to the original signal.

Figures 6A-6C show a third embodiment of the method of KLT coding of the present invention. In this embodiment, the dimension of the signal subspace is not known *a priori.* In practice, the eigenstructure of most signals tends to vary considerably over time. In such cases reconstructing the signal is challenging. Therefore, it is desirable to have a mechanism for adjusting the signal subspace dimension to accommodate signal variations. One approach is to estimate all N eigenvectors, in which case no search direction vector is used. An advantage of this approach is that the eigenvectors found are those of the sample autocorrelation matrix.

Figure 6A shows the steps performed at the transmitter in the method of the third embodiment. In step S610, the KLT basis vector matrix $\hat{Q}$ and the KLT eigenvalue matrix $\hat{\Lambda}$ are initialized to the N by N identity matrix.

In step S612, the transform coefficients y_n are calculated from the previously estimated basis vector matrix $\hat{Q}_{n-1}$, prior to expansion, and the original signal x_n as in Equation (2).

In step S614, the transform coefficients $\bar{y}_n$ are quantized to produce $\hat{y}_n$.

In step S616, the mean squared error ρ and the signal subspace dimension k are initialized.

In step S618, the original signal frame is reconstructed using the initial signal subspace dimension k to produce $\hat{x}_n$.

In step S620, the mean squared error is determined from the reconstructed signal frame and the original signal frame, according to Equation (6):

$$\rho \equiv \frac{||x_n - \hat{x}_n||^2}{||x_n||^2} \qquad (6)$$

In step S622, the signal subspace dimension k is incremented by 1. The dimensions of the subspace are increased until enough basis vectors are present to meet the predetermined mean squared error threshold MSE_{max}, i.e., the basis vectors adequately span

the signal space. If, however, the dimension N of the vector space is reached and the mean squared error threshold MSE_{max} is still not met as inquired in step S624, then the following steps are performed.

In step S626, the columns of the KLT basis vector matrix $\hat{Q}_n$ are orthonormalized.

In step S628, the dimension of the subspace k is reset to 1.

In step S630, the KLT transform coefficients are determined for the reset subspace.

In step S632, the KLT transform coefficients are quantized.

If, in step S624, the N-dimensional vector space is not exceeded or the mean squared error threshold is met, then step S634 is performed. If the mean squared error still does not meeting the threshold, steps S618-S634 are repeated at a higher subspace dimension.

In step S634, if the mean squared error threshold has been met, however, then the optimum signal space dimension r_{opt} (also indicating the number of KLT coefficients) is set in step S636 to k-1.

In step S640, the quantized transform coefficients $\hat{y}_n$ and the optimum signal subspace dimension r_{opt} are transmitted to the receiver. Note that he number of bits allocated to encode each KLT transform coefficient may be predetermined or calculated using, for example, the optimal scheme given by Equation (9). Moreover, additional optional information may be transmitted to the receiver along with the KLT transform coefficients and this information may include data regarding the bit allocation scheme.

In step S642, matrix H is calculated. H is a unitary transformation of the autocorrelation matrix of $\hat{y}_n$, as shown in Figure (7):

$$H = \gamma\hat{\Lambda}_{n-1} + \hat{y}_n\hat{y}_n^T \qquad (7)$$

in which γ is a constant between 0 and 1 and $\hat{\Lambda}_{n-1}$ is the estimated eigenvalue matrix. H then defines a generalized eigenvalue problem as shown in Equation (8):

$$H\hat{Q}_n = \hat{Q}_n\hat{\Lambda}_n. \qquad (8)$$

In step S644, using standard techniques, the generalized eigenvalue problem is solved for $\hat{Q}_n$ and $\hat{\Lambda}_n$. Thus the KLT basis vectors are estimated at the transmitter.

Steps S612-S644 are repeated for all additional signal frames.

Figure 6B shows the steps performed at the receiver in the method of the third embodiment. In step S650, the KLT basis vector matrix $\hat{Q}$ and the KLT eigenvalue matrix $\hat{\Lambda}$ are initialized to the N by N identity matrix.

In step S652, the receiver receives the KLT transform coefficients and the signal subspace dimension (also indicating the number of KLT coefficients) from the transmitter. Note that additional optional information may also be received at this step, including information regarding the bit allocation scheme used to encode the KLT transform coefficients.

In step S654, the KLT transform coefficients are used to reconstruct the original signal frame from Equation (5) based on the transform coefficients corresponding to r_{opt}, in which the transform coefficients for signal subspace dimensions greater than r_{opt} are set to zero.

In step S656, matrix H is calculated according to Equation (7).

In step S658, the KLT basis vector matrix and corresponding eigenvalues of the original signal frame are estimated using Equation (8). Thus the receiver can estimate the KLT basis vectors and use them to reconstruct the original signal frame without having received the basis vectors from the transmitter.

Steps S652-S658 are repeated for all additional signal frames.

Figure 6C shows an exemplary algorithm for performing KLT coding in the third embodiment.

Figure 7 is a graph showing an exemplary result of KLT coding using the method of the third embodiment of the present invention. Figure 7 shows an original and reconstructed signal obtained using the quantized KLT transform coefficients without transmitting the basis vectors. The mean squared error is minimal as can be seen by the closeness of the two signals.

Figures 8A-8C show a fourth embodiment of the method of KLT coding of the present invention. In this embodiment, rather than updating the reduced autocorrelation matrix F with the KLT coefficients, the sample autocorrelation matrix is updated with the reconstructed signal frame $\hat{x}_n$. Moreover, instead of updating $\hat{R}_n$ on a frame-by-frame basis, we can update it on a sample by sample basis by concatenating $\hat{x}_{n-1}$ with $\hat{x}_n$. This enables a more accurate estimate of the sample autocorrelation matrix since more signal frames are used in its computation.

Figure 8A shows the steps performed at the transmitter in the method of the fourth embodiment. In step S810, the KLT basis vector matrix $\hat{Q}$ is initialized to the N by N identity matrix, $\hat{x}_n$ is initialized to a zero vector of length N, and the sample autocorrelation matrix $\hat{R}$ is initialized to the N by N identity matrix multiplied by a small constant less than 1.

In step S811, the transform coefficients y_n are calculated from the previously estimated basis vector matrix $\hat{Q}_{n-1}$, prior to expansion, and the original signal x_n as in Equation (2).

In step S812, the number of bits allocated to encode each transform coefficient is calculated using Equation (9):

$$b_k = B + 0.5\log_2 \frac{[\hat{\Lambda}_{n-1}]_k}{\prod_{j+1}^{r_{opt}^{-1}} \left[\hat{\Lambda}_{n-1}\right]_k} \qquad (9)$$

where b_k is the number of bits allocated to the k^{th} transform coefficient, B is a constant, and $[\hat{\Lambda}_{n-1}]_k$ is the k^{th} eigenvalue. The bit allocation in Equation (9) is the standard rule for minimizing mean-squared error.

In step S814, the transform coefficients y_n are quantized to produce $\hat{y}_n$.

In step S816, the mean squared error ρ, the signal subspace dimension k, and the bit allocation index b are initialized.

In step S818, the original signal is reconstructed at the initial signal dimension k to produce $\hat{x}_n$.

In step S820, the mean squared error is determined for the reconstructed signal and the original signal, as in Equation (10):

$$\rho \equiv ||\hat{x}_n - x_n||^2 \qquad (10)$$

In step S822, the signal subspace dimension k is incremented by 1. The dimensions of the subspace are increased until enough basis vectors are present to meet the mean squared error threshold, i.e., the KLT basis vectors adequately span the signal space. If, however, the

dimension N of the vector space is reached and the mean squared error threshold is still not met as inquired in step S824, then the following steps are performed.

In step S826, a predetermined bit allocation is used.

In step S828, the bit allocation index b is incremented.

In step S830, the dimension of the subspace k is reset to 1.

In step S832, the transform coefficients are determined for the reset subspace.

In step S834, the KLT transform coefficients are quantized.

In step S824, if the N dimensional vector space is not exceeded or the mean squared error threshold is met, then the process goes to step S836. If the mean squared error still does not meet the threshold and bits have successfully been allocated for coding the transform coefficients, e.g. $b<2$, steps S818-S836 are repeated at a higher subspace dimension.

In step S836, if either the mean squared error threshold has been met or the bit allocation has not been successful, however, then step S838 is performed. If, in step S838, the bit allocation index does not equal 2, the optimum signal space dimension r_{opt} (also called the number of KLT coefficients) is set in step S839 to $k-1$.

In step S840, if the bit allocation index equals 2, the optimum signal space dimension r_{opt} is set to N, the dimension of the vector space, and then, in step S842, reduced until $\hat{y}_n(r_{opt}) \neq 0$.

In step S844, the quantized transform coefficients $\hat{y}_n$, the optimum signal subspace dimension r_{opt}, and the bit allocation index b are transmitted to the receiver.

In step S846, the signal sample vector $\vec{w}$ is updated to include $\hat{x}_{n-1}$ and $\hat{x}_n$.

In step S854, the autocorrelation matrix $\hat{R}_{n-1,m}$ is updated for the mth signal sample ($m = 1,\ldots,N$) from $\vec{w}$ in Equation (11):

$$\hat{R}_{n-1,m} = \gamma \hat{R}_{n-1,m-1} + ww^T \qquad (11)$$

$\hat{R}_n$, the autocorrelation matrix after all N vectors of $\vec{w}$ are used, is then put into the generalized eigenvalue problem as shown in Equation (12):

$$\hat{R}_n \hat{Q}_n = \hat{Q}_n \hat{\Lambda}_n . \qquad (12)$$

In steps S858, using standard techniques, the generalized eigenvalues problem is

solved for $\hat{Q}_n$ and $\hat{\Lambda}_n$. Thus the KLT basis vectors are estimated at the transmitter.

Steps S811-S858 are repeated for all additional signal frames.

Figure 8B shows the steps performed at the receiver in the method of the fourth embodiment. In step S864, the KLT basis vector matrix $\hat{Q}$ is initialized to the N by N identity matrix, $\hat{x}_n$ is initialized to a zero vector of length N, and the sample autocorrelation matrix $\hat{R}$ is initialized to the N by N identity matrix multiplied by a small constant less than 1.

In step S866, the number of bits allocated are calculated using Equation (9).

In step S868, the KLT transform coefficients, the signal subspace dimension (also indicating the number of KLT coefficients), and the bit allocation index are transmitted to the receiver from the transmitter. If the bit allocation index does not indicate that the bit allocation was calculated using Equation (9), e.g. $b=0$, then the predetermined bit allocation is used in step S870.

In step S872, the signal is reconstructed using the quantized transform coefficients as in Equation (5).

Steps similar to the transmitter steps S846-S858 are performed at the receiver in steps S874-S886 to estimate the KLT basis vectors after each signal frame is reconstructed. As such, the receiver can estimate the KLT basis vectors and reach the same estimate as the transmitter. Hence, the receiver can estimate the KLT basis vectors and use them to reconstruct the original signal successfully without having received the basis vectors from the transmitter.

Steps S864-S886 are repeated for all additional signal frames.

Figure 8C shows an exemplary algorithm for performing KLT coding in the fourth embodiment.

Figure 9 is a spectrogram of an original speech signal and the reconstructed signal at two different bit allocations, as derived according to the fourth embodiment. The spectrogram shows the signal frequency over a time period. At both allocations, the reconstructed signals are very close to the original signal. In addition, minimal degradation of the signal is experienced.

Figures 10A-10C show a preferred fifth embodiment of the method of KLT coding of the present invention. In this embodiment, the transmitter computes the KLT basis vectors based on the actual, unquantized signal frame x_n. Additionally, in this embodiment, the KLT

coefficients are computed using the KLT basis vectors derived from all of the signal frames up to and including the current signal frame x_n. In the first four embodiments, the KLT coefficients are computed using the KLT basis vectors derived from the signal frames up to, but not including, the current frame (eigenvectors of $\hat{R}_{n-1}$).

Figure 10A shows the steps performed at the transmitter in the method of the fifth embodiment. In step S1010, the KLT basis vector matrix Q is initialized to the N by N identity matrix and the autocorrelation matrix R is initialized to the N by N identity matrix times a small constant less than 1.

In step S1012, the autocorrelation matrix R_n is calculated using the previous value R_{n-1} and the current signal frame x_n.

In step S1014, using standard techniques, a generalized eigenvalue problem is solved for Q_n and Λ_n.

In step S1016, the KLT transform coefficients y_n are calculated from signal frame x_n and the KLT basis vector matrix.

In step S1018, the mean squared error ρ and the signal subspace dimension k are initialized.

In step S1020, the original signal frame is reconstructed using the initial signal subspace dimension k to produce $\hat{x}_n$.

In step S1022, the mean squared error is determined from $\hat{x}_n$ and x_n according to Equation (6).

In step S1024, the signal subspace dimension is incremented by 1.

In step S1026, if the mean squared error ρ exceeds a predetermined value MSE_{max}, steps S1020-S1026 are repeated. Otherwise, step S1028 is performed.

In step S1028, the optimum signal subspace dimension r_{opt} is set to $k-1$.

In step S1030, the KLT transform coefficients y_n are quantized to give $\hat{y}_n$.

In step S1032, the quantized KLT transform coefficients y_n and the optimum signal subspace dimension r_{opt} are transmitted to the receiver. Note that he number of bits allocated to encode each KLT transform coefficient may be predetermined or calculated using, for example, the optimal scheme given by Equation (9). Moreover, additional optional information may be transmitted to the receiver along with the KLT transform coefficients and this information may include data regarding the bit allocation scheme.

Steps S1012-S1032 are repeated for all additional signal frames.

Figure 10B shows the steps performed at the receiver in the method of the fifth embodiment. In step S1050, the KLT basis vector matrix $\hat{Q}$ is initialized to the N by N identity matrix and the autocorrelation matrix $\hat{R}$ is initialized to the N by N identity matrix times a small constant less than 1.

In step S1052, the KLT transform coefficients and the signal subspace dimension (also indicating the number of KLT coefficients) are received from the transmitter. Note that additional optional information may also be received at this step, including information regarding the bit allocation scheme used to encode the KLT transform coefficients.

In step S1054, a counter m is initialized.

In step S1056, a value ϵ measuring a matrix norm is initialized to be greater than a predetermined matrix norm value ϵ_{max}.

In step S1058, the original signal frame is reconstructed using the initial signal subspace dimension k to produce $\hat{x}_n$.

In step S1060, the autocorrelation matrix $\hat{R}_n$ is calculated based on the value of the counter m, a predetermined parameter M, and $\hat{x}_n$.

In step S1062, using standard techniques, a generalized eigenvalue problem is solved for $\hat{Q}_n$ and $\hat{\Lambda}_n$. Depending on which eigenvalue solver is used, the sign of the eigenvectors in $\hat{Q}_n$ must be checked for consistency with those previously stored or initialized $\hat{Q}_{n-1}$.

In step S1064, the change ϵ in the KLT basis vector matrix is computed using a standard matrix norm according to Equation (13):

$$\epsilon \equiv \| \hat{Q}_n - \hat{Q}_{n-1} \| \qquad (13)$$

In step S1066, the current value of the KLT basis vector matrix $\hat{Q}_n$ is stored.

In step S1068, an inquiry is made whether the change ϵ in the KLT basis vector matrix is greater than the predetermined value ϵ_{max}. If so, steps S1058-S1068 are repeated. If not, step S1070 and subsequent steps are performed.

In step S1070, the counter m is incremented.

In step S1072, an inquiry is made whether the counter m exceeds the predetermined value M. If not, steps S1056-S1068 are repeated. Otherwise, no further steps are performed.

Thus the receiver can estimate the KLT basis vectors and reached the same estimate as the transmitter. Hence, the receiver can estimate the KLT basis vectors and use them to

reconstruct the original signal successfully without having received the basis vectors from the transmitter.

Figure 10C shows an exemplary algorithm for performing KLT coding in the fifth embodiment.

Figure 11 shows an exemplary KLT coding system of the present invention. At the transmitter 10, an original signal frame x_n is transformed by a KLT transformer 1100 into KLT transform coefficients y_n. The KLT transform coefficients are quantized at the quantizer 1110 to yield the signal $\hat{y}_n$. As a result of quantization and possibly discarding transform coefficients that are zero, the quantized signal $\hat{y}_n$ that enters the encoder 1120 is significantly reduced from the original signal x_n. The encoded signal is then sent along the channel. Depending on the specific embodiment, additional information may be sent as well. For example, the codebook index used in the second embodiment, the bit allocation index used in the fourth embodiment, etc.

At the receiver 11, the encoded signal is received through the channel into the decoder 1130. The signal is decoded, yielding the quantized transform coefficients $\hat{y}_n$. The original signal frame is reconstructed at the KLT inverse transformer 1140 to produce the reconstructed signal frame $\hat{x}_n$.

The mechanisms and processes set forth in the present description may be implemented using a conventional general purpose microprocessor programmed according to the teachings in the present specification, as will be appreciated to those skilled in the relevant art(s). Appropriate software coding can readily be prepared by skilled programmers based on the teachings of the present disclosure, as will also be apparent to those skilled in the relevant art(s).

The present invention thus also includes a computer-based product which may be hosted on a computer readable storage medium and include instructions which can be used to program a computer to perform a process in accordance with the present invention. The storage medium can include but is not limited to, any type of disk including floppy disk, optical disk, CD ROMS, magneto-optical disks, ROMS, RAMS, EPROMS, EEPROMS, flash memory, magnetic or optical cards, or any type of media suitable for storing electronic instructions. The instructions can be further read from other computer readable media such as transmission media of computer communication devices (e.g., Ethernet and wireless (e.g., IR or RF) adapters). Listings for sample implementations in MATLAB© of the first, second,

and fourth embodiments are listed in the Appendix.

Numerous modifications and variations of the present invention are possible in light of the above teachings. For example, the structure of the algorithms used to implement the invention may take on any desired form. Further, in each embodiment, the number of KLT coefficients transmitted or received and the corresponding number of estimated KLT basis vectors can be as few as one. It is therefore to be understood that within the scope of the invention, the invention may be practiced otherwise than as specifically described herein.